SHORT-RANGE STRUCTURE OF CLOUDS STUDIED BY HIGH RESOLUTION PHOTOGRAPHY FROM THE SURFACE

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MOTIVATION

Clouds have a strong impact on Earth's radiation budget: -45 W m^{-2} shortwave; +30 W m^{-2} longwave.

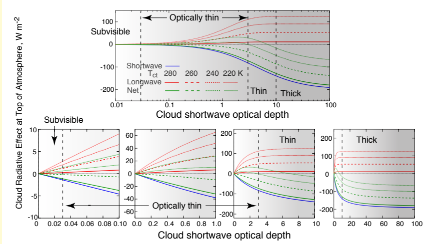
Slight change in cloud amount or properties could augment or offset greenhouse gas induced warming – cloud feedbacks.

Accurate representation of cloud radiative effects in climate models is essential.

Clouds exhibit structure on small scales not resolved by satellite imagery.

OPTICALLY THIN CLOUDS HAVE STRONG RADIATIVE EFFECTS

Dependence on shortwave optical depth and cloud-top temperature
24-Hour average cloud radiative effect, north central Oklahoma, at equinox



HOW THIN IS AN "OPTICALLY THIN" CLOUD?

If cloud optical depth is 3 . . .

- Number of scattering events is 3 . . .
  - Number of drops in vertical column is 1.5 . . .
    - Liquid water path (for 15 µm diameter drops) is 10^{-3} cm or **10 g m^{-2}**.

If cloud optical depth is 0.3 . . .

- Number of scattering events is 0.3 . . .
  - Number of drops in vertical column is 0.15 . . .
    - Liquid water path (for 15 µm diameter drops) is 10^{-4} cm or **1 g m^{-2}**.

Thin indeed. But these clouds are radiatively important!

MEASUREMENTS

COMMERCIALLY AVAILABLE HIGH-RESOLUTION CAMERA

1200 mm equivalent 35 mm focal length; f/5.6

$180,000 $350

Nominal resolution 6 µrad (6 mm at 1 km)

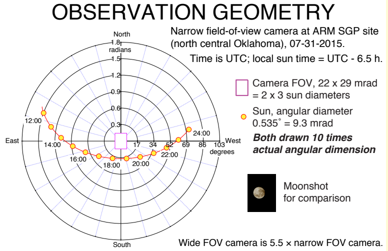
STRENGTHS AND ADVANTAGES

High resolution: 6 µrad nominal (6 mm at 1 km); 20 µrad actual.
Many independent measurements: 3456 × 4608 = 16 M pixel.
High dynamic range: 16 bit.
Multispectral: Three wavelengths nominal, Red, Green, Blue.
Black background of outer space: Minimal surface effects.
Readily available data acquisition hardware and software.
Available, easy-to-use image processing software.
Simplicity: Get going right away.
Low cost.
Lots of data!

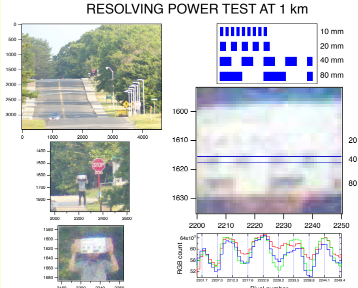
WEAKNESSES AND LIMITATIONS

Two-dimensional only.
Daytime only.
Limited wavelength range.
Small fraction of sky; extremely local.
Aerosol masquerades as cloud.
Lots of data!

OBSERVATION GEOMETRY



RESOLVING POWER TEST AT 1 km

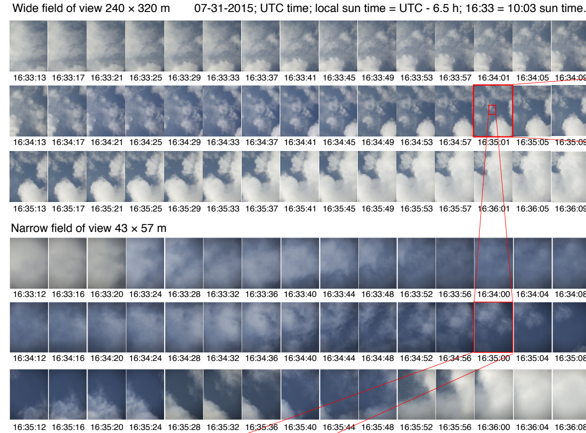


Actual resolution 20 µrad (20 mm at 1 km)

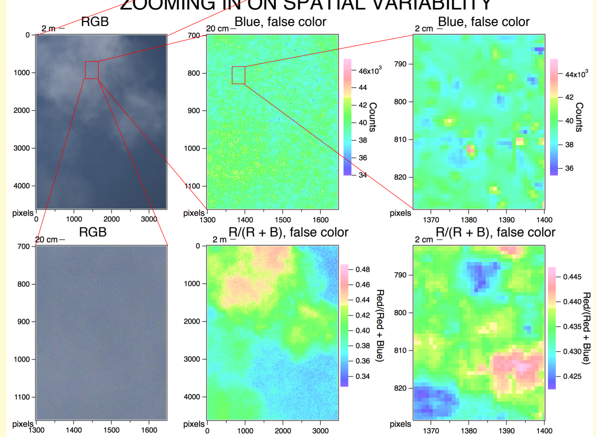
SOME INITIAL RESULTS

ZOOMING IN, IN SPACE AND TIME: THREE MINUTES IN OKLAHOMA

Wide field of view 240 × 320 m 07-31-2015; UTC time; local sun time = UTC - 6.5 h; 16:33 = 10:03 sun time.

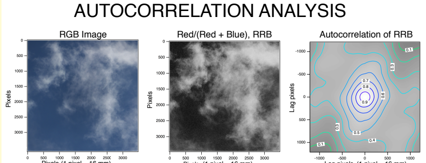


ZOOMING IN ON SPATIAL VARIABILITY



SPATIAL VARIATION

AUTOCORRELATION ANALYSIS



Autocorrelation distance ~1000 pixels in this example corresponds to ~16 m.

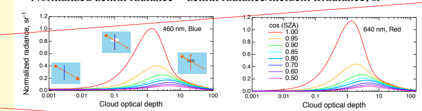
Such short autocorrelation distances are commonly found in these analyses.

THEORY

RADIATION TRANSFER CALCULATIONS

Calculations with DISORT

Normalized zenith radiance = zenith radiance/incident irradiance, sr^{-1}



Zenith radiance initially ***increases*** with increasing cloud optical depth COD, before decreasing with optically thick clouds.

SCALING OF INTENSITIES FROM IMAGES

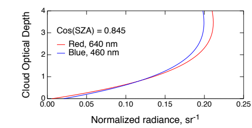
Identify cloud-free and bright cloud regions of image. ***Scaled normalized radiance*** R_s is evaluated from measured count rate C as

$$R_s = R_{min} + \frac{C - C_{min}}{C_{max} - C_{min}}(R_{max} - R_{min})$$

C_{min} and C_{max} from images; R_{min} and R_{max} from radiation transfer calculations.

DETERMINING CLOUD OPTICAL DEPTHS FROM IMAGES

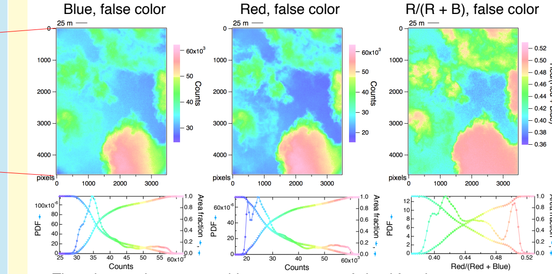
Scaled radiances are inverted at a given solar zenith angle to yield cloud optical depth COD as a function of normalized radiance at each of the two wavelengths:



Inversion is valid for optically thin clouds, COD $\lesssim 3$.

CLOUD FRACTION

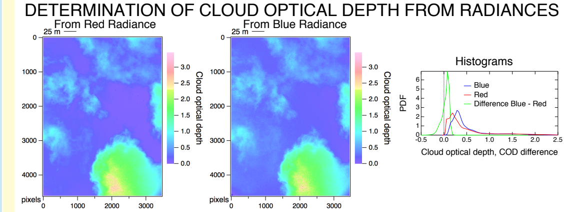
ALTERNATIVE MEASURES OF CLOUDINESS AND CLOUD FRACTION



There is no unique or unambiguous measure of cloud fraction.
Red/(Red + Blue) color ratio is very sensitive to optically thin clouds.

CLOUD OPTICAL DEPTH

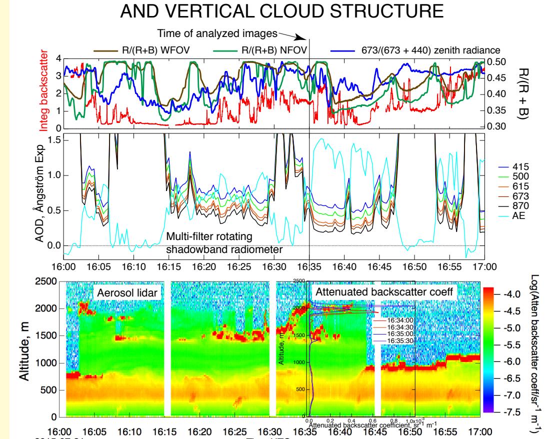
DETERMINATION OF CLOUD OPTICAL DEPTH FROM RADIANCES



Cloud optical depth is determined with precision of about 0.1 OD over range 0 to 3.
Close agreement for COD from Red and Blue radiances supports the method.

TIME DEPENDENCE

MULTIPLE MEASURES OF CLOUD EFFECTS ON RADIANCE AND VERTICAL CLOUD STRUCTURE



Clouds exhibit high R/(R + B), optical depth, lidar return; low Ångström exponent.
Different quantities are broadly coherent but exhibit different time responses mainly because of differing FOV.

CONCLUSIONS

- ***Photography of clouds from the surface provides*** a novel way of looking at clouds and their radiative effects at ***much higher resolution than other cloud imaging techniques***.
- Readily available commercial cameras provide a ***resolution of about 20 µrad*** (corresponding to 20 mm for cloud base at 1 km), ***3 orders of magnitude higher than typical satellite products***.
- ***Cloud properties are highly variable in space (a few meters or less) and time (a few seconds or less)***.
- ***Autocorrelation distances are commonly of order a few meters***.
- ***Cloud area fraction***, a widely used product of surface-based and satellite observations, ***is inherently dependent on choice of threshold***.
- ***Cloud optical depth can be accurately retrieved*** at native resolution of the camera ***for optically thin clouds, optical depth*** $\lesssim$ ***3***.

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